REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL REPORT

4. TITLE AND SUBTITLE
Indium Mono-Ion Oscillator

5. FUNDING NUMBERS
61102F
2301/DS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Physics
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8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 95 - 0320

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-92-J-0052

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

Accesion For	
NTIS CRA&I	X
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

13. ABSTRACT (Maximum 200 words)

SEE FINAL REPORT ABSTRACT

19950427 137

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

~~Annual~~ Final Technical Report: 1993-1994

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1.0 Introduction

During the third (and final) year of the "Indium Mono-Ion Oscillator" grant, our goal of loading and observing a single indium ion was realized. In order to achieve this result, we relied on the development work of previous years; the "background suppression system" developed earlier was found to be particularly useful. We also began the design and construction of the all-solid-state "clock laser" system. Our intent is to replace all of the bulky argon and dye lasers with solid state systems; this will allow considerable reduction in the size and power consumption of the resulting optical frequency standard.

2.0 Single Ion Apparatus

During the summer of 1994, single indium ions were first observed in our laboratory at the University of Washington. They were trapped in a small "Paul-Straubel"[1] (single ring) radiofrequency trap consisting of a single loop of tantalum wire made by twisting two short pieces of 100 μm diameter wire together to form a loop whose inside diameter is $\approx$1 mm (Fig. 1). The trap was coated with "Aerodag" graphite coating to minimize the possible stray DC fields caused by "patch effects"; these fields can dramatically increase the Doppler shifts by causing the ion to be strongly driven at the trapping frequency (10 MHz in this case). The graphite should also reduce instrumental scattering from the trap electrode (although this benefit was not particularly evident in our trap). The ring was excited with about 600 V at 10 MHz in order to trap the ions; this results in a "secular" frequency (free oscillation frequency) of about 1 MHz. The trap was enclosed in a quartz vacuum chamber (see Fig. 1) which was pumped to a pressure of $\approx 4\times 10^{-11}$ torr with a triode vacion pump.

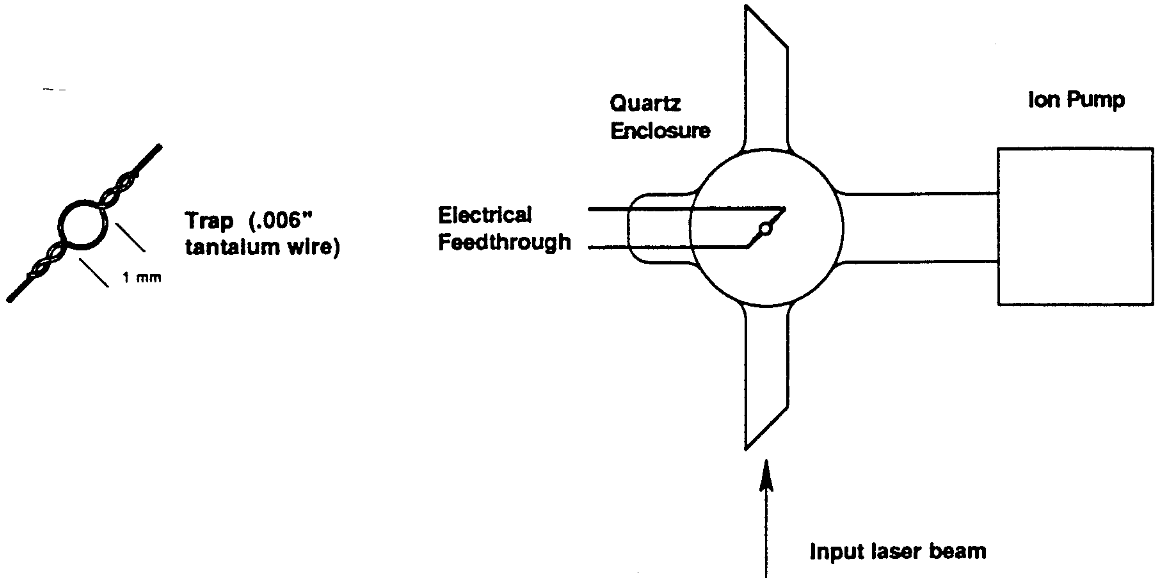

Fig. 1 End view of apparatus used to trap single indium ions. An enlargement of the twisted-wire trap appears on the left. The fluorescence from the single indium ion is directed out of the plane of the figure and is collected by an f/2 mirror and photomultiplier system. Not shown are the indium oven and tungsten filament used for loading ions.

3.0 Signals from Single Ions

Single ions were loaded into the trap by weakly turning on the indium oven and electron gun while down-tuning the laser about 200 MHz below the expected ion resonance frequency. Despite the fact that the natural width[2] of the ion resonance is only about 360 KHz, this large initial downtuning was found to be necessary, presumably because the downtuned laser more effectively cooled the initially Doppler broadened ion. This process was facilitated by fairly exact knowledge of the ion resonance frequency. The frequency was set using a saturated tellurium resonance whose width is about 20 MHz; the earlier measurements on Doppler broadened In^+ clouds had established this frequency within the previously quoted error of 5 MHz.

Even though the 5^1S_0-5^3P_1 ("cooling") transition of a single cold indium ion is saturated when irradiated with about 5 μW focused to a 50 μm diameter spot (this takes account of the 10 MHz laser linewidth), initial cooling of a hot ion just after loading is considerably facilitated if more cooling power is available. We found that we needed about 50 μW to easily load single ions. This power was provided by a BBO doubling crystal placed in a ring enhancement cavity (without the cavity, only about 5 μW was available). An overall block diagram of the single ion apparatus, showing the enhancement cavity, appears in Fig. 2.

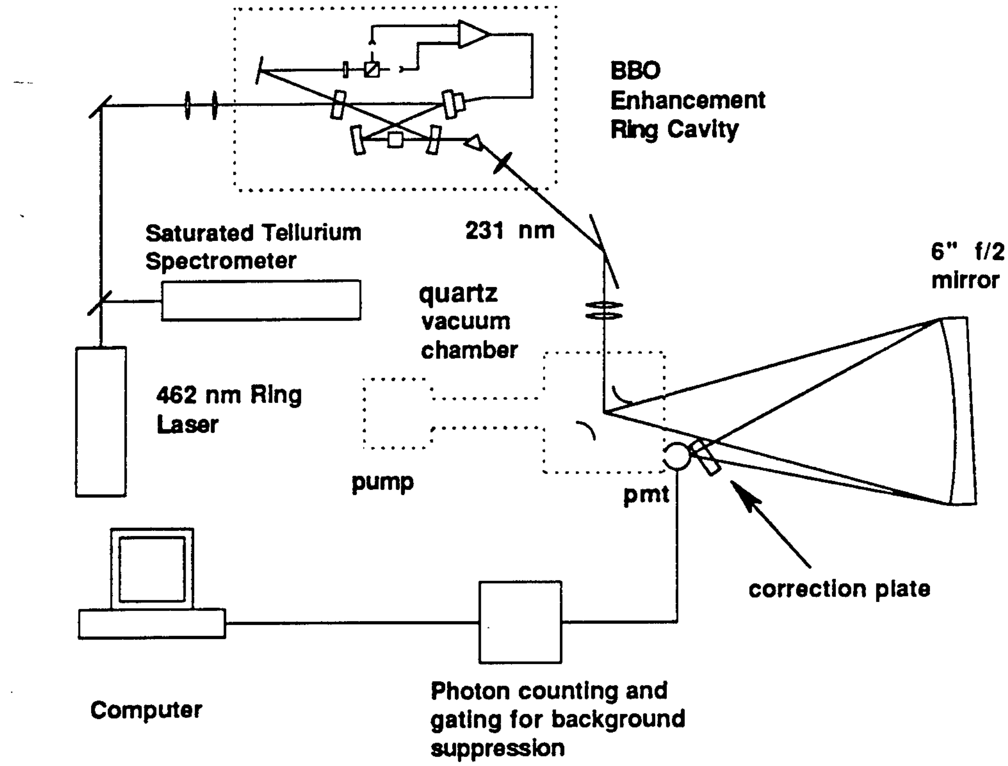

Fig. 2 Block diagram of single indium ion apparatus showing enhancement cavity for efficient uv generation.

As shown in Fig. 2, the fluorescent light from a single indium ion is collected with a slightly off-axis f/2 mirror. While this system is quite economical for its aperture (an equivalent corrected lens system would cost more than \$10,000), it suffers a bit from aberrations. The result is that the background is quite high, easily overwhelming the relatively weak single ion signal. (The ion fluorescence is due to an intercombination line and is therefore about 100 times weaker than the fluorescence observed from previously studied ions, such as barium, magnesium, beryllium or mercury.)

To suppress the background, the UV light was 100% amplitude modulated with a 1 MHz square wave and the PMT signal was gated with a square wave 180° out of phase with the modulating signal. Since the background light appears essentially instantaneously, there should be no observed background. The fluorescence, however, is due to a decay from a level with a .44 μs lifetime[2]; there will therefore be a substantial ionic fluorescence during the time that the PMT is gated on. Using this scheme, we have been able to suppress the background by a factor of about 500; this is accompanied by a roughly five-fold reduction in the signal. For the integration times we used, the result was an improvement in the signal to noise by a factor of about 5, making the single ion signal easily visible.

Our first single ion signal appears at the top of Fig. 3. This was taken using the baseline suppression system. Immediately afterward, an identical run was taken without baseline suppression; this appears at the bottom of the figure. The improvement in signal to noise provided by baseline suppression should be evident. After this first loading experience, it became rather easy to load single ions.

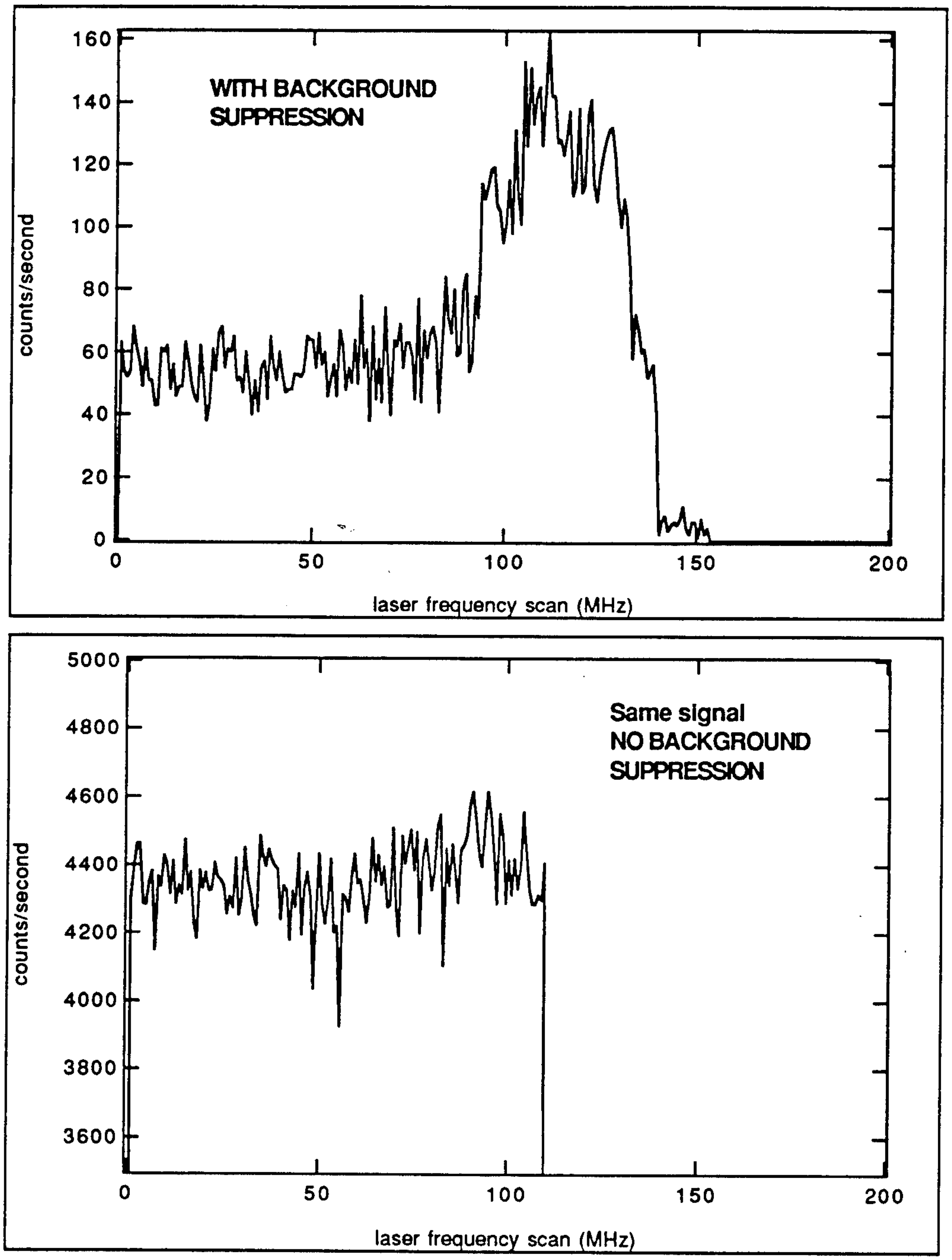

Fig. 3 First observed single ion resonance with (top) and without (bottom) baseline suppression.

At present, there is no direct evidence that the observed ion signals are from individual ions. Absolute confirmation that the ion signals are from single ions requires the observation of "quantum jumps"[3] , as has been done with other species (particularly barium and mercury). The "jumps" occur naturally in the indium system: they are due to magnetic dipole decays from the 5^3P_1 "cooling" level to the 5^3P_0 "clock" level; this transition will occur after a few minutes of strong excitation of the cooling level. Unfortunately, observation of the "jumps" requires the ability to observe single ion signals with a small integration time (less than .1 s), since the lifetime[2] of the "clock" level is .14 s. We currently lack the signal to noise ratio to do this; with improved optics, we should be able to observe "quantum jumps". However, there is compelling indirect evidence that we have single ions. The first is the reproducibility of the observed fluorescence level - the fluorescence is nearly always the same (within about 20%). Secondly, on a number of occasions, the ion has stayed in the trap overnight. It has been our experience (with barium and magnesium ions) that the ion-ion heating that occurs with more than one ion always prevents multiple ions from staying in the trap for much longer than a few minutes.

Although the natural width of the indium "cooling" transition is about 360 kHz, the narrowest linewidths we have observed are about 14 MHz. We feel that this is due mostly to the width of the cooling laser: the dye laser width has been measured to be about 5 MHz, resulting in a $\approx$10 MHz linewidth after doubling. The observed width does, however, set an upper bound on the ion temperature. This is about .5 mK for the narrowest observed lines (assuming cooling to the Doppler limit and a laser-limited linewidth). A plot of one of our better lines appears in Fig. 4.

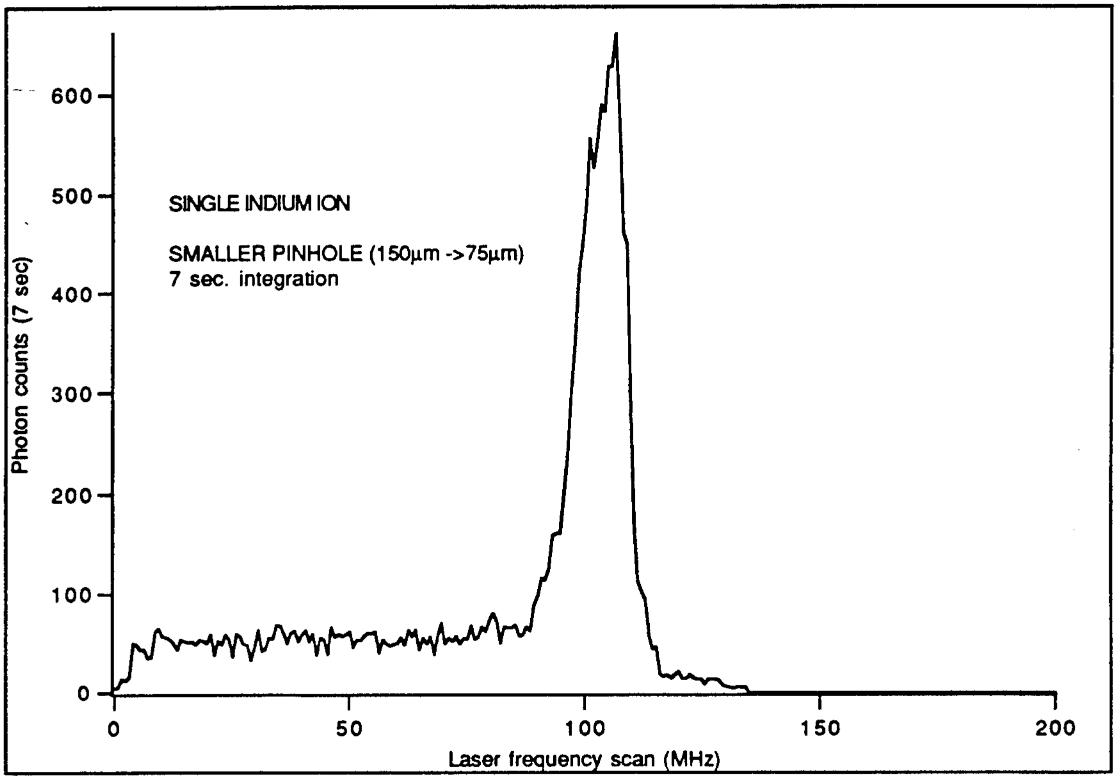

Fig. 4 Single ion resonance with 7 s integration time. The asymmetry is due to laser heating above resonance, causing the fluorescence to suddenly drop. The full width at half maximum is laser-limited and is about 14 MHz.

4.0 Clock Laser

Currently single indium ions can be routinely loaded and cooled to very low temperatures; the next step is to use these ions as a "single-ion resonator" to construct an ultrahigh resolution frequency standard. As has been shown[4] , such a standard is free from virtually all sources of broadening (first and second order Doppler broadening, transit-time broadening, collisional broadening and broadenings due to interactions with electric and magnetic fields.) It should be possible with indium to realize the natural width of its "clock" transition, which is about 1 Hz.

There are several possible approaches to the construction of a very narrow laser capable of exciting the 5^1S_0-5^3P_0 "clock" transition at 236 nm. We have chosen an approach which appears to be the simplest, using state of the art diode laser and frequency doubling technology. It uses an external-cavity diode laser which is frequency doubled in two stages to 236 nm. Construction is under way of several parts of the system using funds provided by the NSF for the establishment of a "Tunable Laser Facility" at the University of Washington.

A block diagram of the entire system appears in Fig. 5. The laser will be supplied by a commercial vendor, which has already provided us with a stable, reliable external-cavity diode laser operating at 649 nm. In the vendor's laboratory, there are reliable versions of these lasers operating at wavelengths (.986 μm) very near to that needed for indium. The .986 μm lasers produce about 30 mW of power - this value will be used in the following estimates, despite the anticipated higher powers which should be available soon. The lasers have a short-term linewidth of under 100 kHz, resulting in a free-running linewidth at 2365Å of well under 1 MHz. It should be straightforward to lock the laser to a highly stable Zerodur cavity; a linewidth of 1 Hz (in 1 s) appears just within reach of current technology.

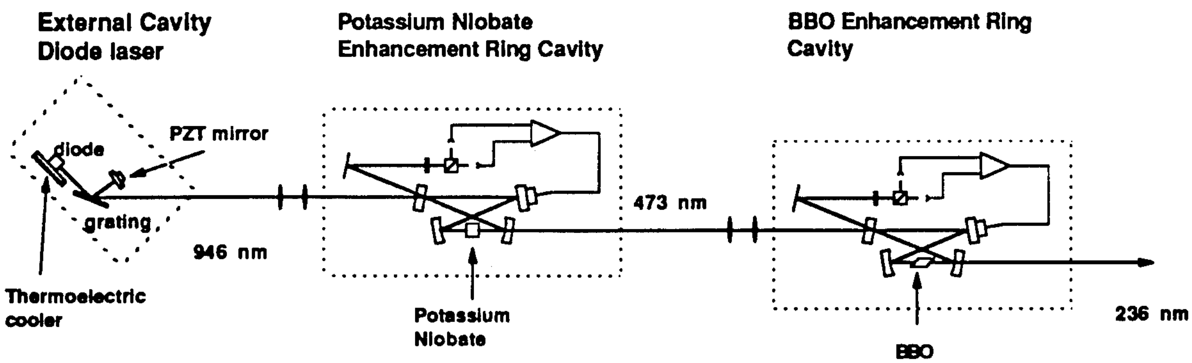

Fig. 5 Apparatus used to generate 236 nm radiation for indium experiment. The lenses in front of each enhancement cavity are used to mode-match the radiation into the cavity. The apparatus shown at the top of the cavities is used to lock the cavities to the laser frequency using the "polarization" scheme.

The enhancement cavities are "bow-tie" configuration ring cavities capable of power enhancement factors of from 30 to 100. The latter factor will require the use of a Brewster-cut doubling crystal and a cavity geometry designed to compensate for both astigmatism and coma (for appropriate choice of "opening angles", the astigmatism and coma generated in the off-axis mirrors are compensated by the inclined faces of the crystal). Since the enhancement cavities are resonant, they will be locked to the laser frequency using the "polarization" scheme[5] , which has the advantage of providing quick and reliable relocking when an unlocking event occurs. Such a scheme is in use in a BBO enhancement cavity in one of our laboratories and it provides nearly "turn-key" operation of the doubling system. Light will be "mode-matched" into both cavities using the lenses shown in the figure.

The first cavity will use a piece of potassium niobate heated to 185° C to double the .946 μm laser light to .473 μm. At this temperature, the phase matching is "noncritical",

which is the requirement for the best doubling efficiency and best output beam quality. The efficiency of a 1 cm length of crystal is about .01/W. Thus, in order to convert a large fraction of the input radiation to the second harmonic, a circulating power of about 1.2 W is needed (this will convert about half of the input power). This requires an enhancement factor of about 40, which can be easily achieved using a AR-coated crystal without concern with the issues of astigmatism or coma.

The second cavity will use a 0.5 cm length of BBO to double the $\approx$14 mW of .473 μm radiation into the UV. At this wavelength, BBO phase-matches (via angle-tuning) at 57° to the optical axis. Based upon a conservative conversion efficiency of 2×10^{-5}/W (measured in our laboratory at a nearby wavelength), an enhancement factor of 100 will provide about 40 μW of radiation at 2365Å. The somewhat elongated output beam (due to walkoff, since the phase-match angle is not 90°) can be made circular with a combination of spherical and cylindrical lenses, using standard techniques. Subject to the availability of funding, it should be possible to construct both the "cooling" and "clock" lasers using these techniques, resulting in a compact single-ion frequency standard with modest power requirements. (It should be possible to dispense with the second enhancement cavity in the "clock" laser once the resonance is found, since the power requirement for exciting the narrow "clock" resonance of a highly localized ion is exceedingly small)

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